On a Solar Power Infrastructure around Moon's South Pole - And Its Critical Role in a Lunar Economy

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If God wanted man to become a spacefaring species,

He would have given man a moon.

Krafft Arnold Ehricke,

father of the first hydrogen-oxygen stage, Centaur

Outline

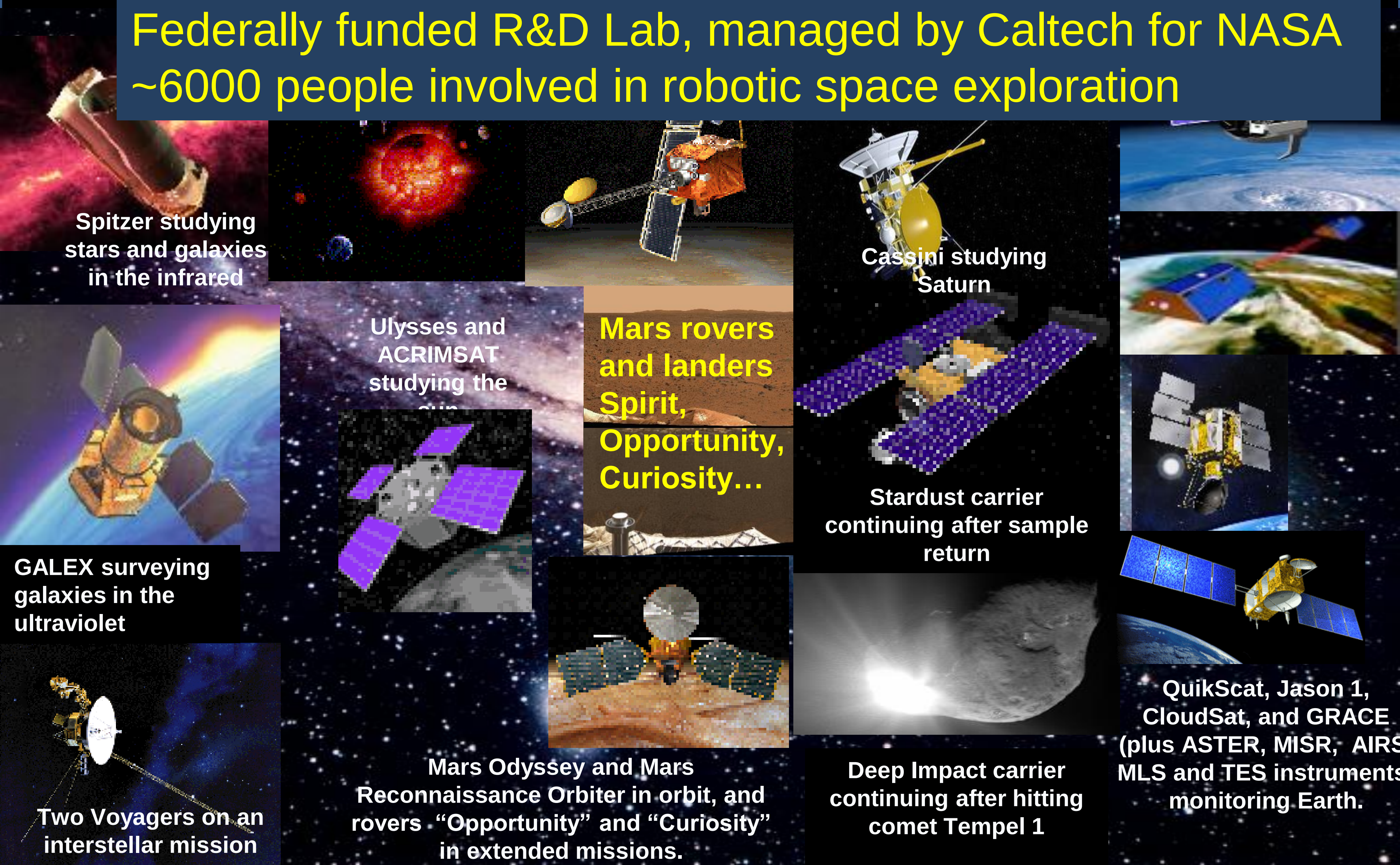
- **Moon's Value Proposition**
  - Local resources and being Earth's spaceport
- **Lunar Economy**
  - Mining, especially for water (LH2, LOX) as propellant for transportation to Mars
  - Infrastructures, especially a solar energy infrastructure
- **Specific Technologies**
  - Robots, for exploration, ISRU/Manufacturing, teams of robots and AI

Jet Propulsion Laboratory (JPL) is NASA's lead center for robotic space exploration

JPL-managed Deep Space Network ensures communications with for all spacecraft beyond the Moon

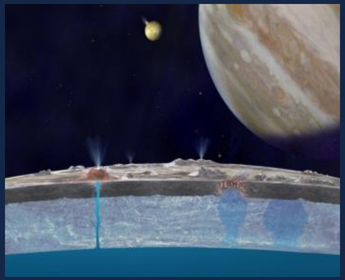
JPL designed, build and operated the first US satellite, Explorer 1

Federally funded R&D Lab, managed by Caltech for NASA
~6000 people involved in robotic space exploration



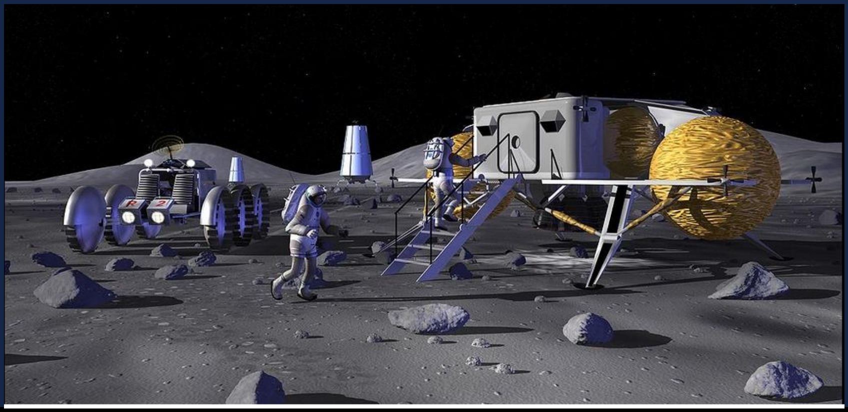
NASA plans for the Moon

- JPL leads the robotic space exploration, driven by space science, to Mars and beyond (Europa Lander)
- Humans to Mars



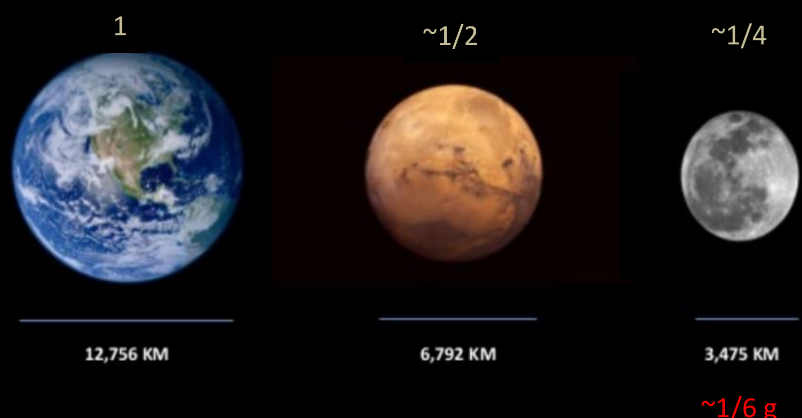

Moon:

- Current vision/plan are to establish a permanent human presence, and prepare for Mars
  - Gateway – a lunar orbit station
- Robotic missions would be precursors, before sending humans



Moon as the logical next step

(More) Affordable –closer (~2.5 vs ~180 days), less dangerous, the logic stepping stone from which to move to farther destinations



Risk reduction for other destinations

– It allows for validation of technologies and mechanisms of international collaboration.

PNAS
Proceedings of the
National Academy of Sciences
of the United States of America

Direct evidence of surface exposed water ice in the lunar polar regions

Shuai Li, Paul G. Lucey, Ralph E. Milliken, Paul O. Hayne, Elizabeth Fisher, Jean-Pierre Williams, Dana M. Hurley, and Richard C. Elphic

PNAS September 4, 2018 115 (36) 8907-8912; published ahead of print August 20, 2018
https://doi.org/10.1073/pnas.1802345115

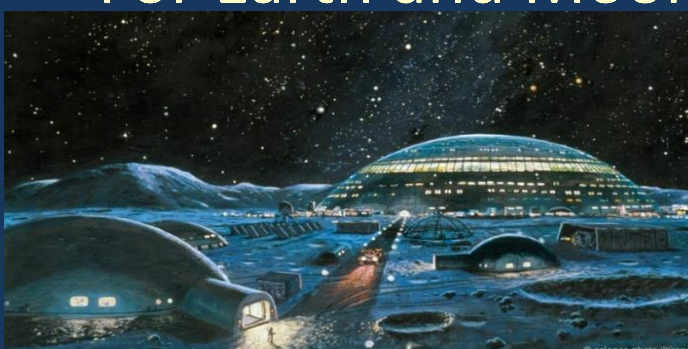
Moon’s value proposition

Resources

Entertainment/tourism

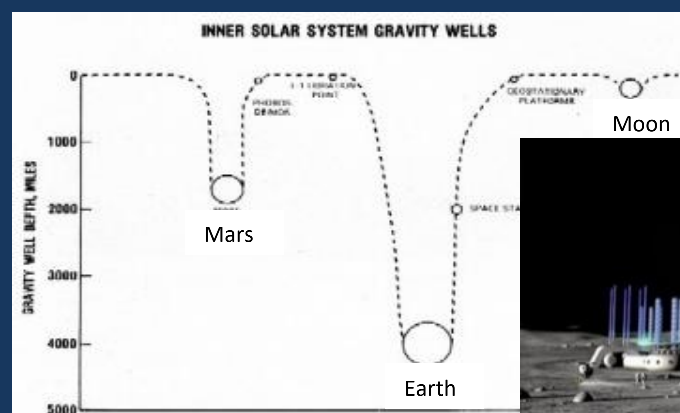
Laboratory for science & tech

- For Earth and Moon



Spaceport

with own production of propellant, liquid hydrogen and oxygen

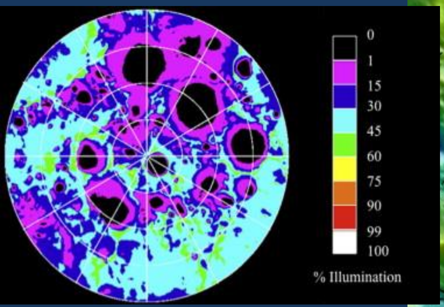


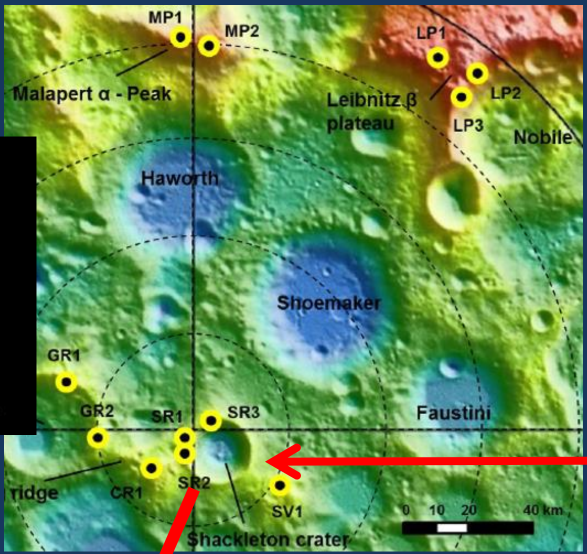
Outpost/Testbed:

- for Mars& beyond missions

Treasure maps at the Lunar South Pole

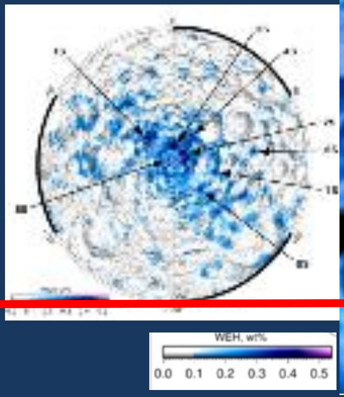
Maps of Sunshine

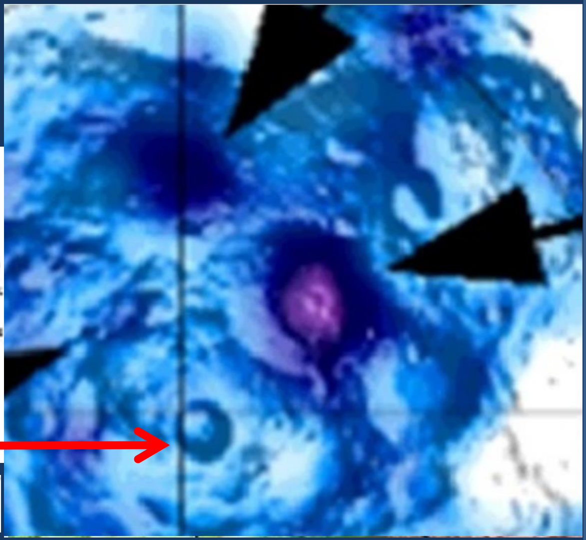




Maps of Water

WEH - Water Equivalent Hydrogen





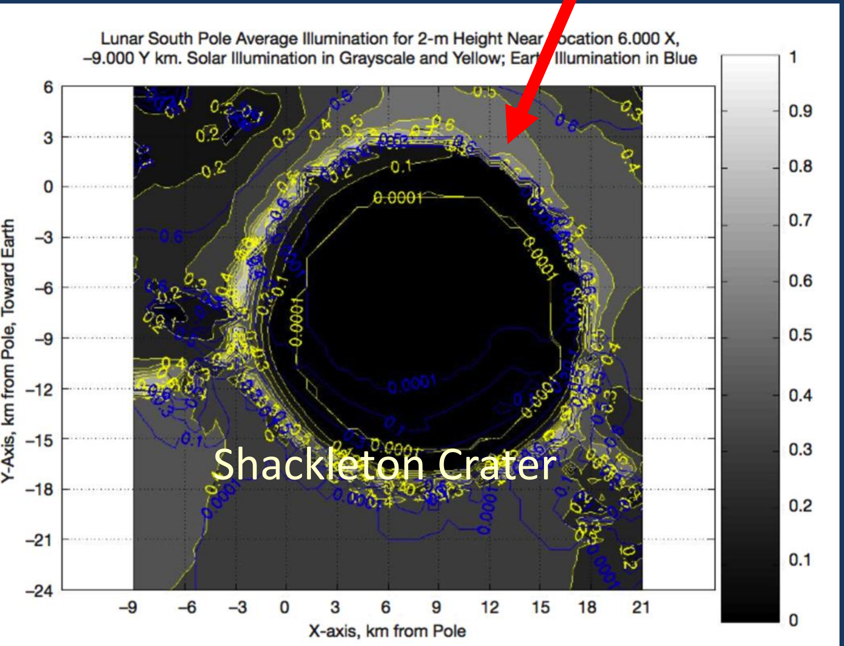


Figure 16. Shackleton Crater yearly average illumination, coarse resolution.

Lunar South Pole has regions of sunlight and regions with water resources next to each other

The rim of the Shackleton Crater is illuminated most of the time; the floor of the crater is permanently shaded, and there is indication of water in the icy regolith

Moon is priority for other agencies

Newsweek

RUSSIA WILL GO TO THE MOON NEXT YEAR WITH FIRST LANDER IN DECADES

BY DAMIEN SHARKOV ON 1/25/18 AT 6:32 AM

Luna 25 - Luna-Glob lander is a planned lunar lander mission by the Russian Federal Space Agency (Roscosmos). It will land near the lunar south pole at the Boguslavsky crater.

MOON DAILY

Russian cosmonaut could ride US spacecraft to Moon for first mission

Moscow (Sputnik) May 07, 2018

The first flight of a Russian cosmonaut to the moon could take place aboard of the US Orion spacecraft in 2024, a

MOON DAILY

China has technological basis for manned lunar landing

Harbin (XNA) Apr 30, 2018

China has the technological basis for a manned lunar landing, says Zhou Jianping, chief designer of China's manned space program. Human exploration of the universe would not stop in low-Earth ...

中国探月 CLEP

Japan, India: plan for lander, rover, sample return, tech demos in support of long-term base.

ESA signs collaboration agreement for commercial Lunar missions ...

https://www.esa.int/.../ESA_signs_collaboration_agreement_for_commercial_Lunar_...

Apr 17, 2018 - Ian Jones remarked that, “This partnership opens a new chapter on the development of international exploration of the **Moon** and beyond.

Planned lunar missions…2016

some dates have slipped but all still in the plans…

Planned	Moon Express (2017) · SpaceIL (2017) · Chang'e 5 (2017) · Astrobotic / Hakuto / AngelicvM / Puli (2017 Chandrayaan-2 (2018) · Chang'e 4 (2018) · EM-1 (Lunar Flashlight / Lunar IceCube / LunaH-Map / SkyFire) (2018) · SELENE-2 (2018) · SLIM (2019) · Chang'e 6 (2020)

Chang'e 5

After successful Chang'e 3 lander (2013) and Yutu rover, China prepares a sample return (2019).

Likely will have first woman on the Moon

First private landers/rovers

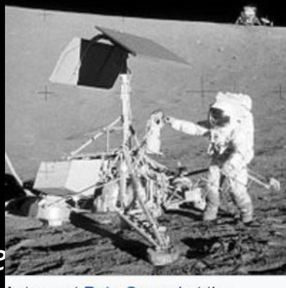
Astrobotics/SpaceX: lander, rover

MoonExpress/Rocketlabs. Masten/ULA

PT Scientists: Rovers, 1st at Appolo 17, second will be at the South Pole

Soviet Luna 2 crash landed in 1959 and Luna 16 did robotic sample return in 1970.

First US rovers on the moon – since 1966, were JPL rovers



Astronaut Pete Conrad at the Surveyor 3 during Apollo 12, 1969. Lunar module in the background.

Deep Space Gateway

September 27, 2017 A research partnership was established between NASA and the Russian age

NASA wants to build a Deep Space Gateway, a space station near the moon to learn about li

working in deep space.

The moon-bound station will serve as a jumping off point for missions to places like Mars.

Partnerships for the Moon

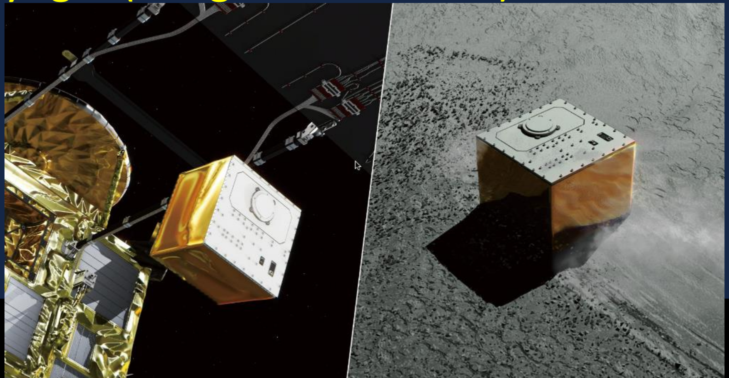
The Moon offers multiple models of shared investment/risk

International Space Station

Conventional partnerships (joint missions) sub-system level within same mission

- Yutu rover has a US instrument, a telescope developed by a lunar institute in Hawaii, USA
- Hayabusa2 has MASCOT rover

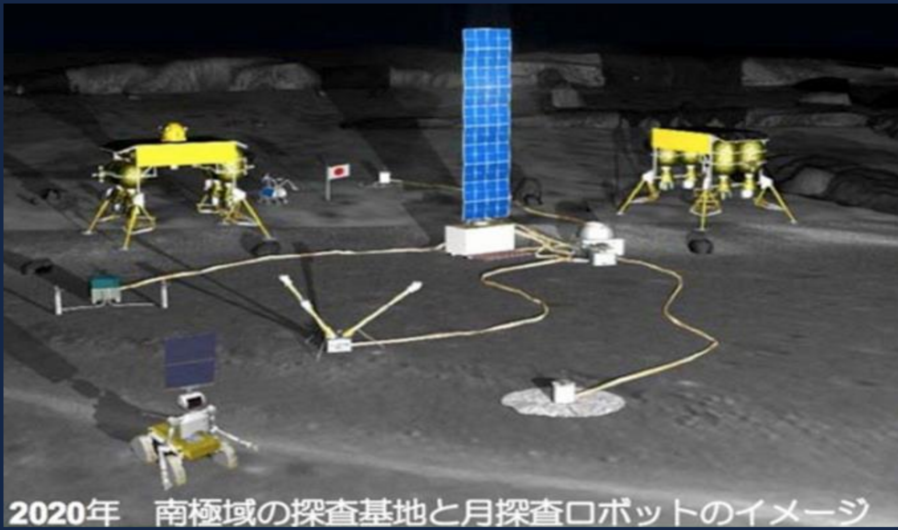
Illustration of MASCOT (DLR/CNES) landing on the surface of Ryugu. (Image credit: JAXA)



Moon Village

Novel forms of partnerships are proposed/emerging: at system level, multi-mission, cooperative.
- Teams of robots could collaborate on the lunar surface.
- Each can be developed/operated/ funded by a different entity

- The *Moon Village* concept, promoted by the European Space Agency (ESA), offers a vision of collaboration via assets owned (and operated) independently, by different nations, yet engaged in mutual support and assistance, in a robotic ecosystem.



Moon Village

Technologically and financially accessible to commercial entities

This scenario also considers – and allows 'space' for the imminent involvement of private companies.

- launch
- tourism
- mining

SpaceX
Elon Musk

Blue Origin
(Jeff Bezos)

This is the most profound factor affecting the future exploration and use of the Moon because of the more flexible – and potentially higher level of - funding.

Paul Allen
StratoLaunch Systems

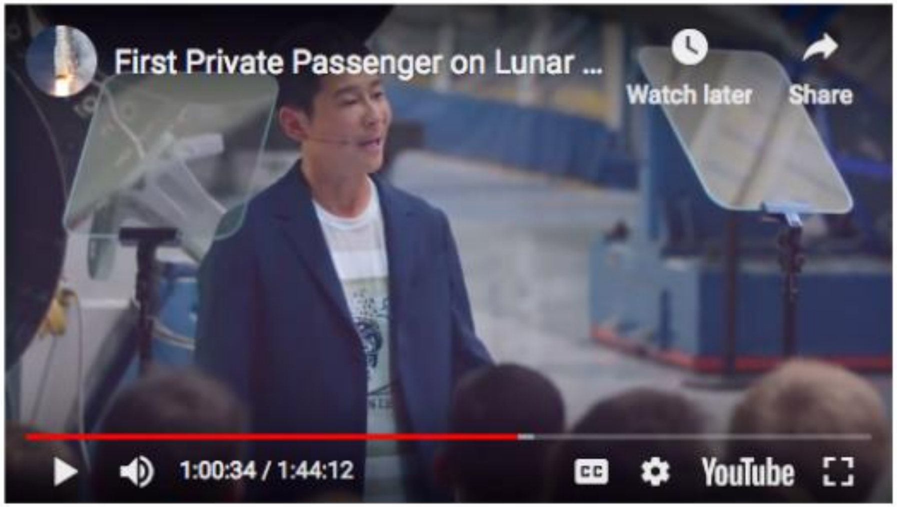
(with Burt Rutan) SpaceShipOne

Virgin Galactic
Richard Branson

SEPTEMBER 18, 2018

FIRST PASSENGER ON LUNAR BFR MISSION

On September 17, 2018, SpaceX announced fashion innovator and globally recognized art curator Yusaku Maezawa will be the company's first private passenger flight around the Moon for 2023. To date, only 24 people have visited the Moon, with the last of them flying in 1972. This first private lunar passenger flight, featuring a fly-by of the Moon as part of a weeklong mission, will help fund development of the BFR vehicle, an important step in enabling access for everyday people who dream of flying to space. Watch a replay of the announcement below.



Opportunities in cis-lunar space

Earth-orbiting satellites proved that one can operate profitable businesses in the space sector (at least in Earth-orbit)

Space Angels

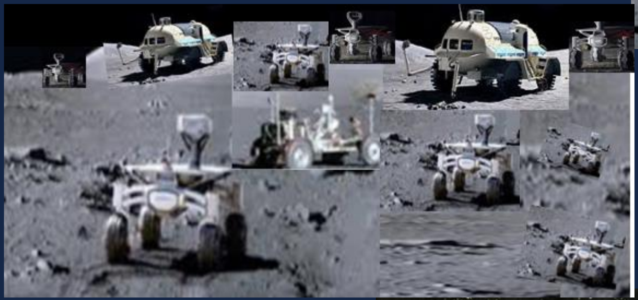
Commercial companies and Private Investment Firms (e.g. ULA, Space Angels, etc.) are analyzing opportunities and investing in mechanisms and businesses that may operate beyond Earth, in cis-lunar space (and one day to the surface of the Moon).

Organizers
Institutional Support
Lunar and Planetary Institute
Universities Space Research Association
NASA Lunar Exploration Analysis Group

Advanced concepts

Telescopes on far side of the Moon (in a crater?)

Moon (robotic) village

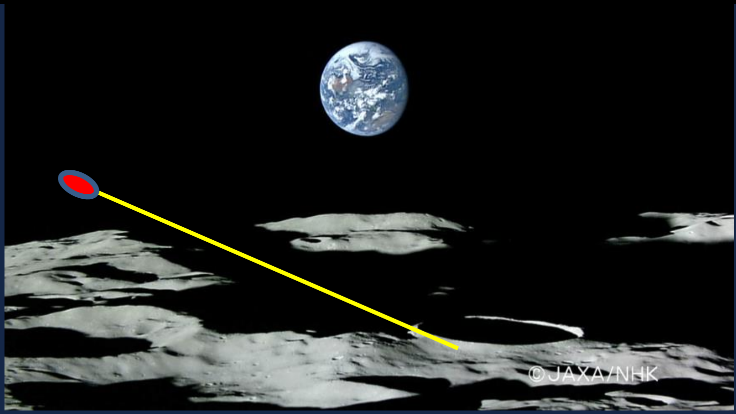


Exploration Caravan

Human presence: Hotel

Key to sustainable/flourishing moon

Lowering costs for lunar missions



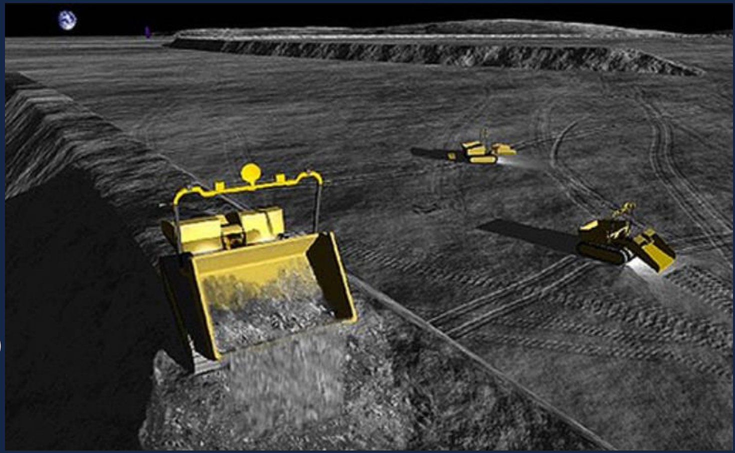
<u>*Access*</u>

Launches with local resources

– Obtain H2 and O2 from lunar regolith

– EM launchers, solar powered

Landing runways of sand/thin regolith



<u>*Power (for launches and more)*</u>

An efficient power infrastructures matched to needs and environment

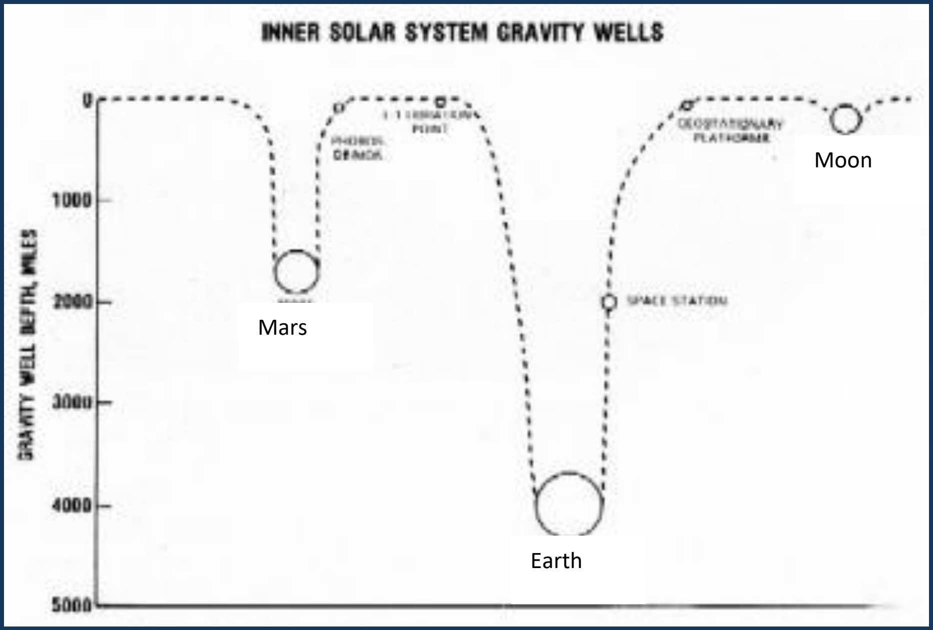
- A solar power infrastructure discussed here

Lunar Economy

- Transportation (to/from and on surface)
  - To Mars with lunar propellant
  - EMG launchers; sandy landing runways, ballistic exchanges
- Mining
- Infrastructure/utilities (energy , communication, construction, life-support)
  - Energy (collection, storage, distribution, installation, service, operation)
- Services (information/data, entertainment, health, maintenance/repair)

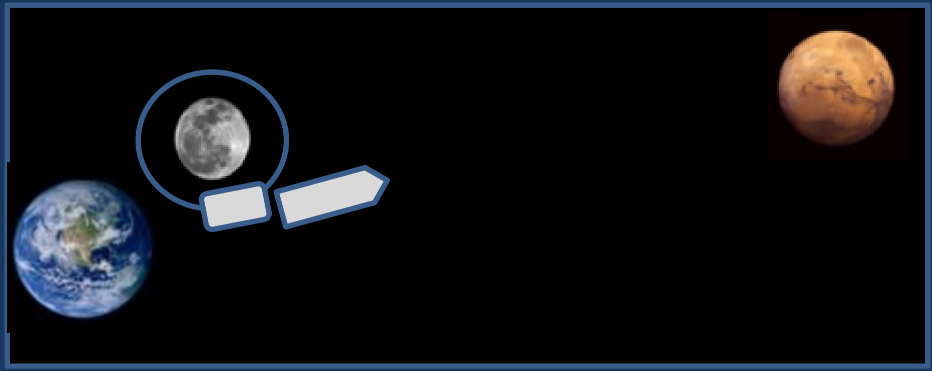
Transportation to/from the Moon -and to/from Mars

Carrying all propellant with you from Earth, or making propellent elsewhere (LO, LH)



Going to Moon/Mars with Earth/Moon made propellent,

- Return with one from Earth
- Return with made on Moon
  - (refuel in a cis-lunar orbit)
- Return with Made on Mars

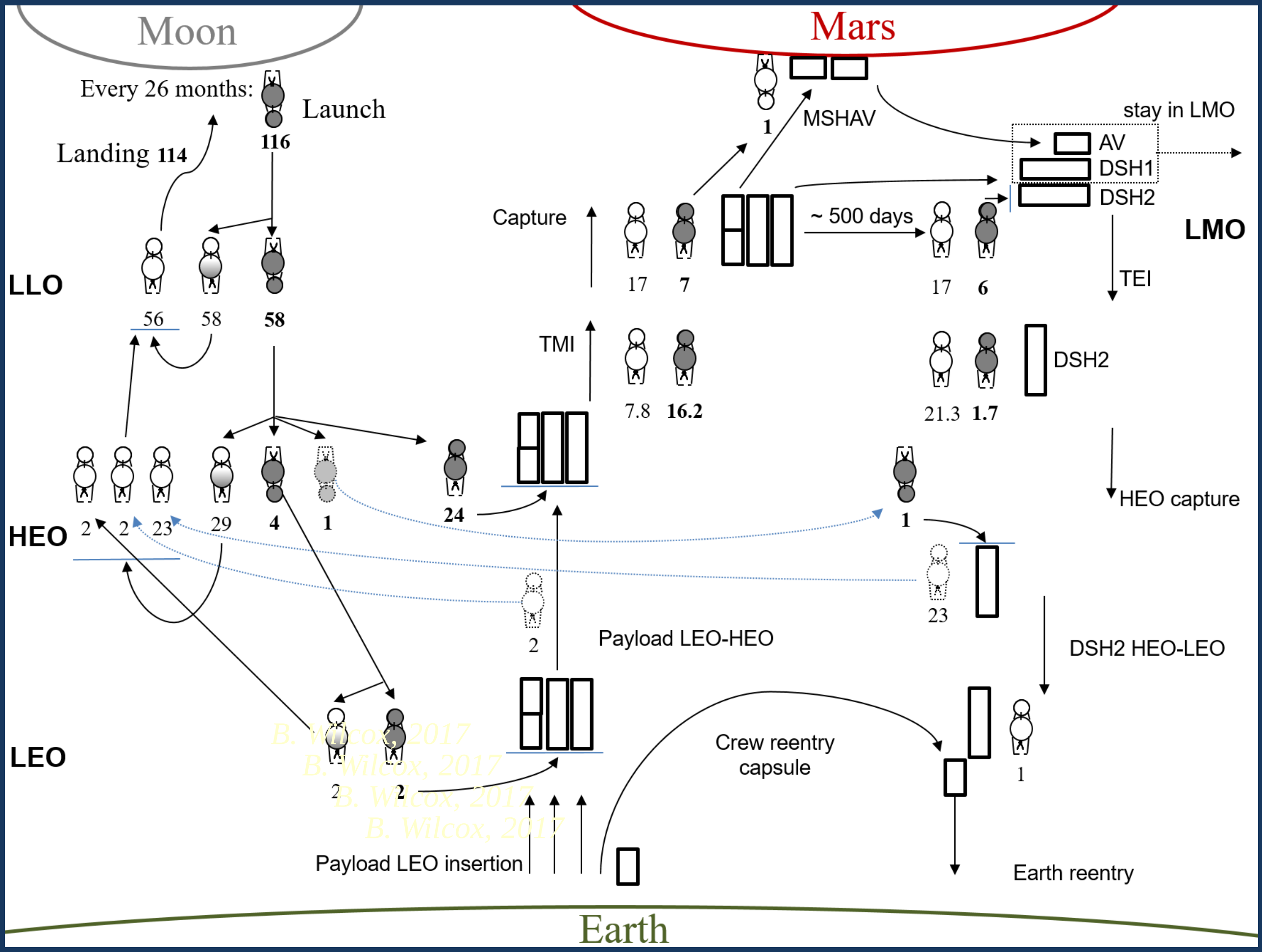


To Mars, with Propellant from the Moon

Idea: Use the moon as a reservoir of propellant for our space voyages.
How much fuel?
How much water?

An affordable human Mars architecture with lunar propellant.

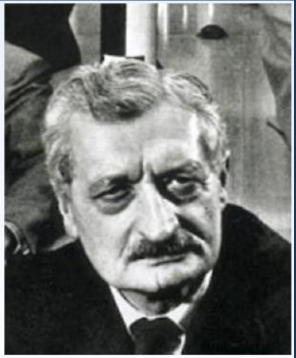
Continuous production on 26-month cycles, delivering 24 full tanks to HEO as needed to propel payload stack to Mars and back.



7.5 tons of $LH_2/LO_{2)}$ *per day are needed*
This requires 10 tons of water per day

Mirrors for the Sun

Mirrors in Space



Father of Rocketry Hermann Oberth.
Image Credit: NASA

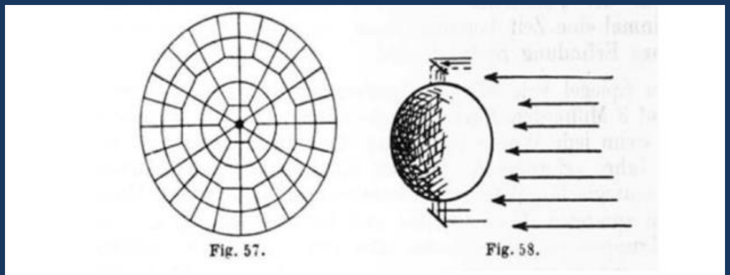
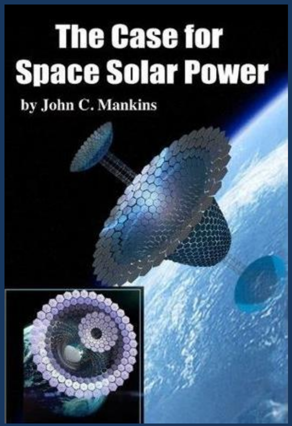


Illustration from 1929 showing the first stages in constructing the space mirror and an illustration from Oberth's original 1923 description, showing the mirror-supporting web and how the mirrors could be used to illuminate and warm the polar regions.

Znamya 2

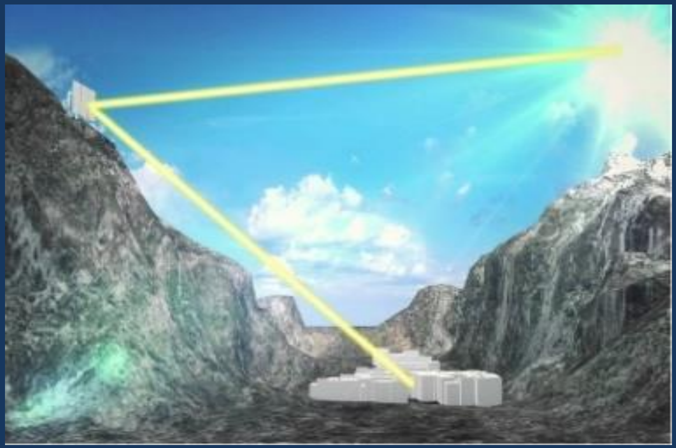
20m-diam
Deployed
successfully

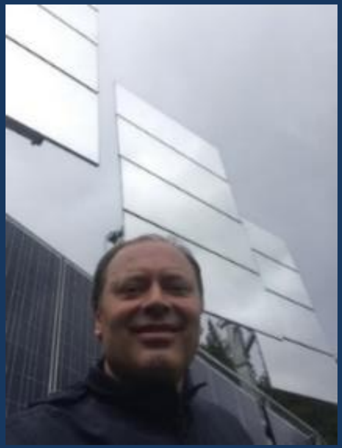
in 1993



Mirrors on Earth

Rjukan, Norway, 3 mirrors, 3x5m each



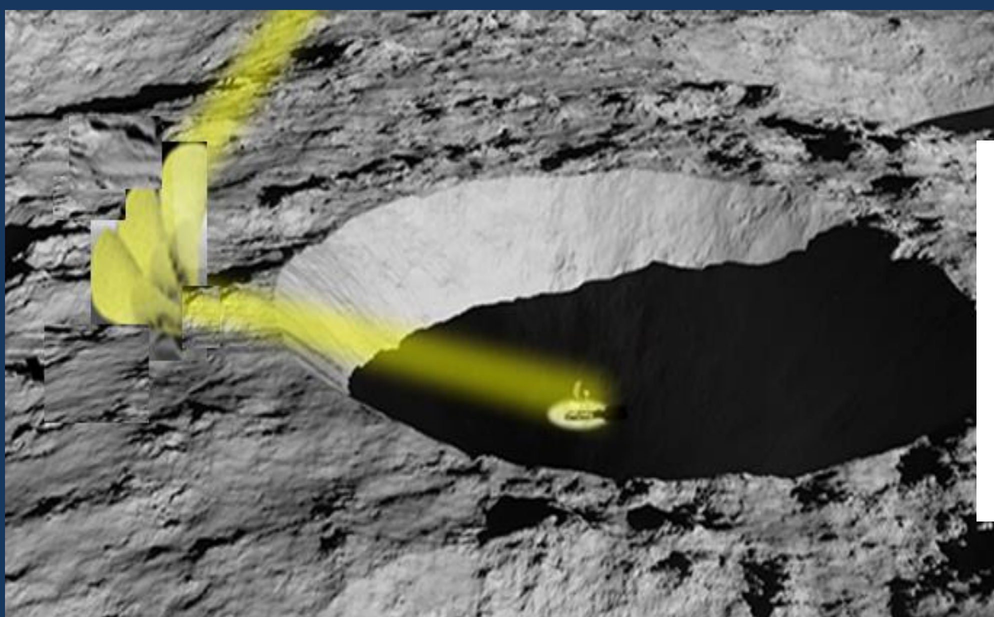


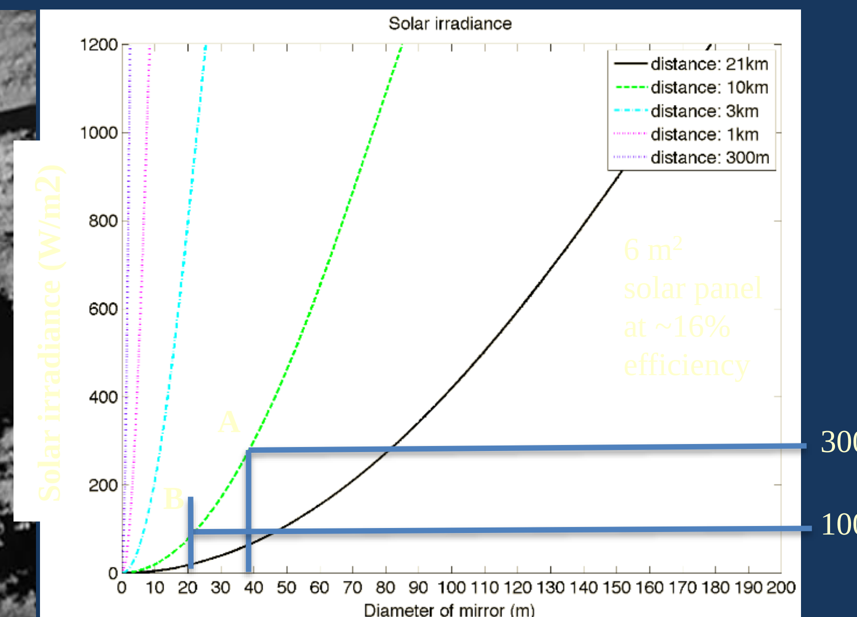
Mirrors on the Moon

TransFormers: - Shape Changing Robotic Reflectors

Transform an extreme environment (cold & dark) into a hospitable one

Placed on the rim of Shackleton Crater, TransFormers would reflect solar energy onto robots operating in the dark cold crater.



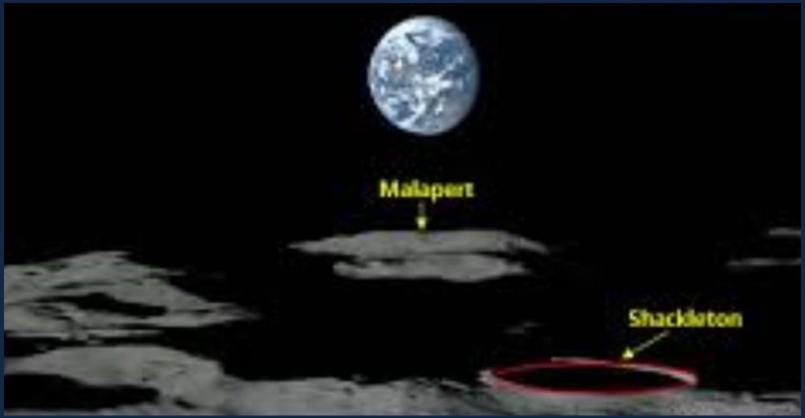


A 40 m diameter TF (1256m²) is needed to provide ~300 W/m² of power at 10 km

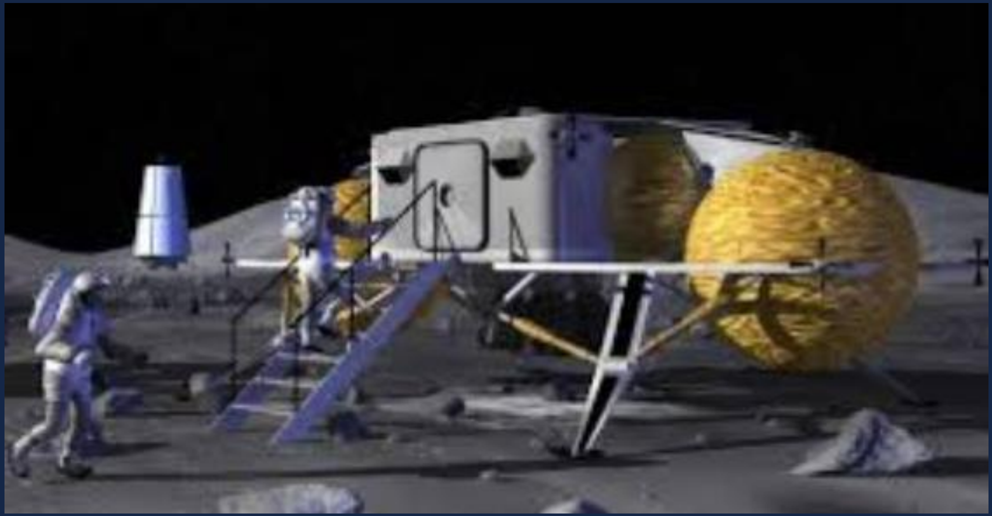
A. Stoica – NIAC I, II TransFormers for Extreme Environments

Technologies: priorities

Key challenge: it's an extreme environment, cold and dark, with no source of energy when the sun is not illuminating

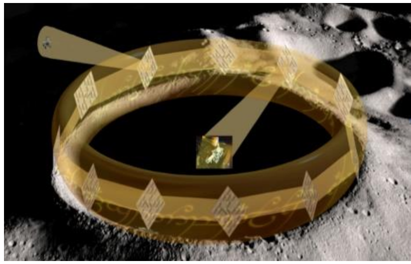


- *Power and communications*



- Life-support

Power needs – in the context of lunar mission scenarios



ISRU

Fuel production (H_2, O_2) to travel to Mars and beyond, affordable

- From icy regolith in permanently shaded craters
- Shackleton crater is a primary candidate (south pole)
- Human Mars Water Production Architecture analysis

Human missions (Spudis et al. 2010)

- <u>Human Power and Logistics Cluster</u>: the power necessary to support human habitation. Part of this cluster would include additional power plants and batteries
- Outside crater, near crater to have easy access to water

Robotic exploration

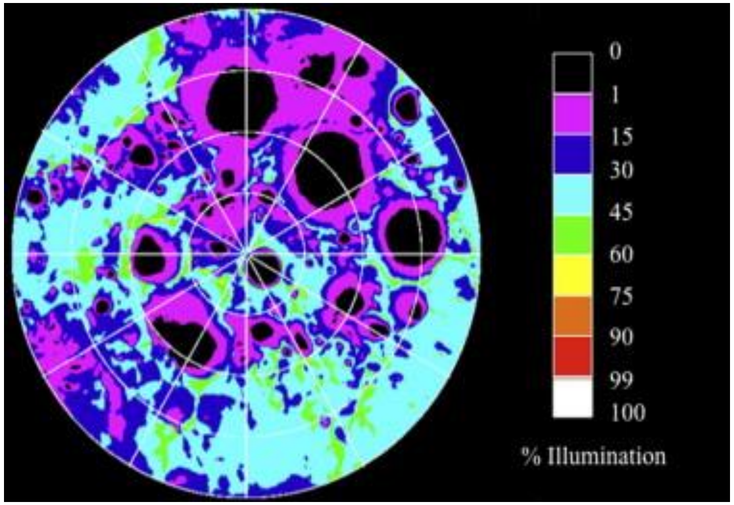
- Robots seeking ice deposits
- Robots doing science
- Can operate only while solar power (SP) or use RTG
- **Planned missions – all SP:** <u>Resolve</u>: SP (JSC, CSA), <u>Icebraker</u>: 80-160W SP (CMU), <u>Resource Prospect</u>: SP(KSC, JSC, Ames)
- Multiple/cooperative scenarios
- Could be powered by same solar power source (reflectors as discussed – in which case multiple assets would be illuminated simultaneously and they would not require each to have its own power/RTG)

Currently we do not have a solution for operating in permanently shaded areas. All areas become shaded at some times and need to hibernate /stop operations

Goal: provide year-round, uninterrupted, to ~10 to 100km + near grid, From a min of ~13 W/m^2 (compensating for heat loses in dark) to full intensity 1.3kW/m^2

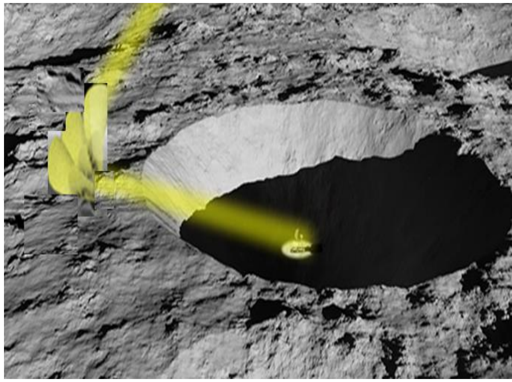
Reflected Solar Power to Area(s) of Interest

- **Concept:** Create power infrastructure at south pole of Moon using system of strategically placed solar reflectors
  - Several locations in south pole region receive sunlight over 80% of the year
  - Multiple coordinated reflectors could redirect sunlight to area(s) of interest to give 100% of the year
  - Reflector system could provide power to multiple regions simultaneously



(Bussey et al. 2010)

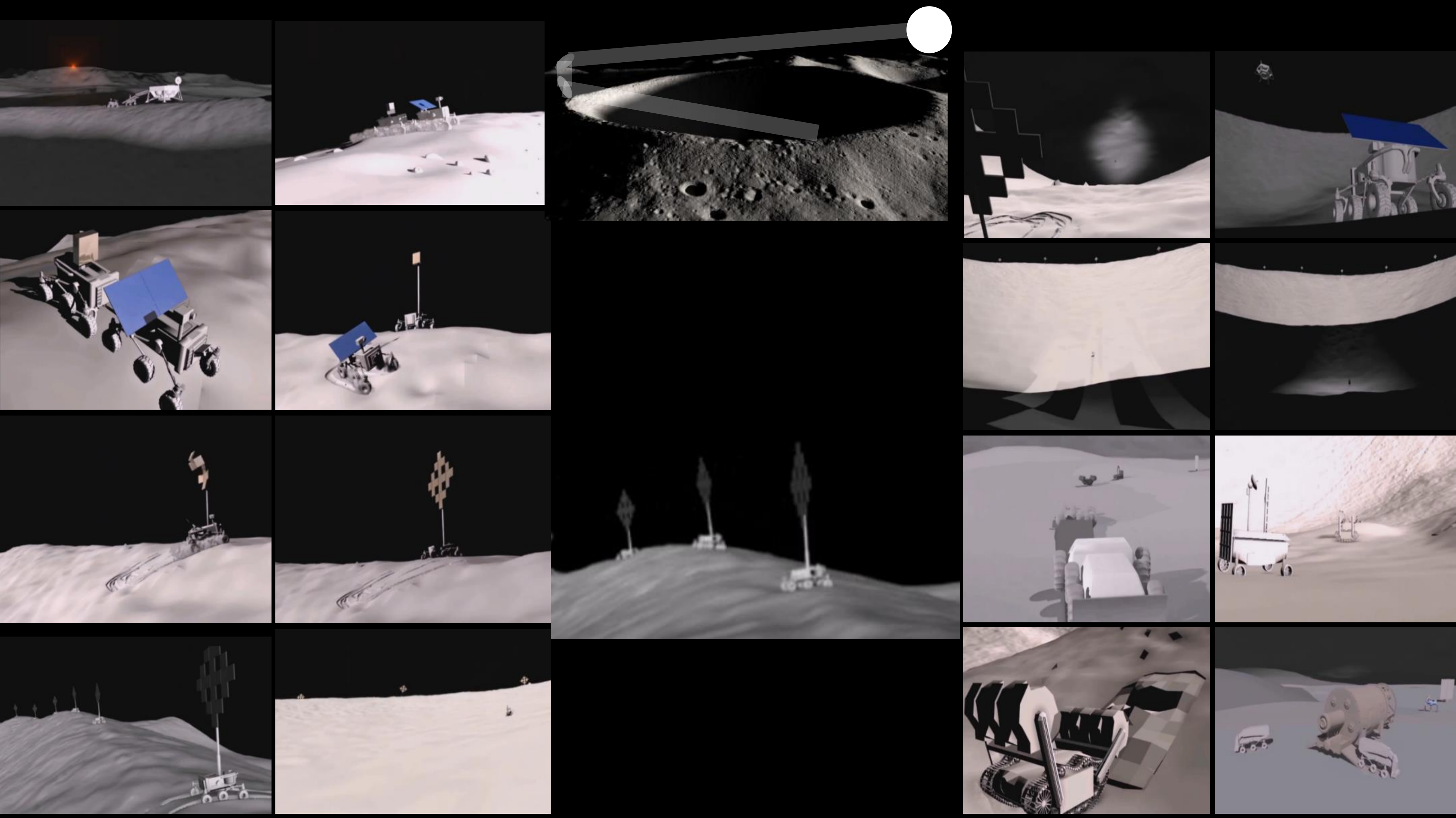
- **NIAC Study Objective:** Determine feasibility of using reflectors to provide *continuous, year-round* access to sunlight to a target area near Shackleton Crater
  - Identify optimal reflector placement locations
  - Size power infrastructure according to ISRU mission requiremen
  - Evaluate structural designs and deployment mechanisms



A Solar power infrastructure at lunar south pole could provide power 100% of the time

Mission Concept

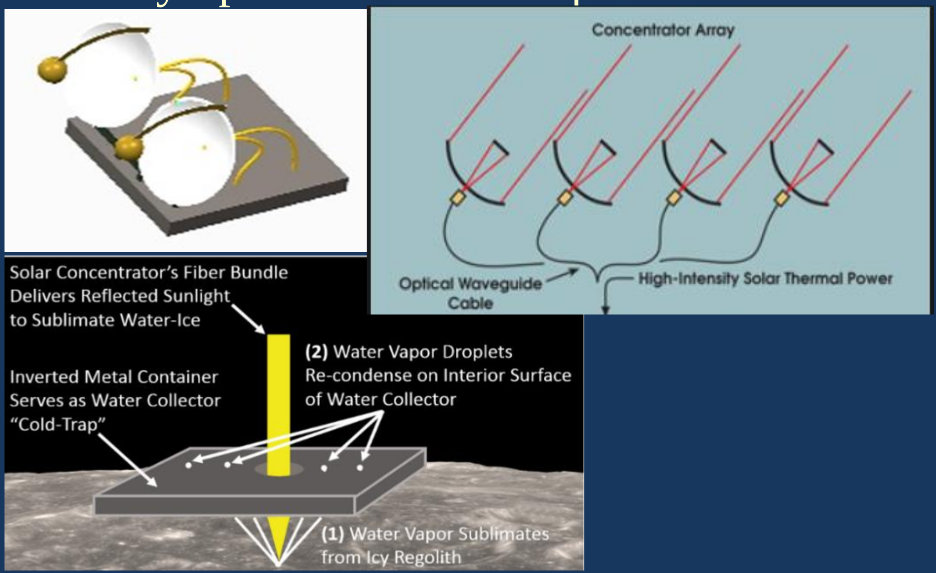
Solar powered operations inside Shackleton Crater



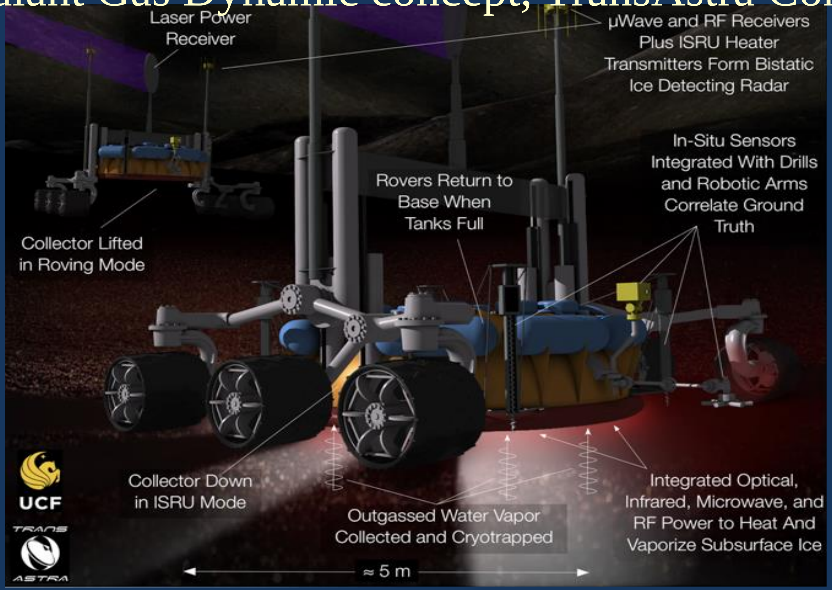
Water from the Rock

How to extract water from regolith? How much power is needed?

Kennedy Space Center concept



Radiant Gas Dynamic concept, TransAstra Corp

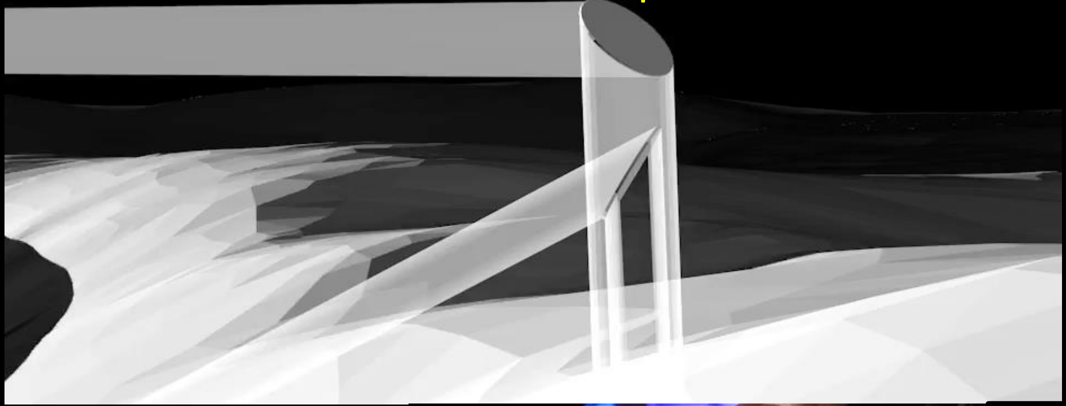


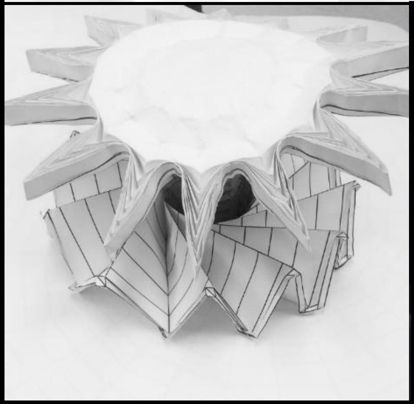
The energy needs to obtain 10 t of water per day:

- The energy (thermal) for water extraction: ranging from 0.54 MW (at 4.7 kJ/g, for 10% water in regolith) to 1.58 MW (at 13.8 kJ/g, for 1% water in regolith).
- The separation through electrolysis (at 18 kJ/g) would require ~2 MW (electric), i.e. ~6 MW solar received from TF assuming ~33% efficiency.

Towers of Light

A 40-m diameter reflector would provide ~1.2 MW   @10km away
100-m diameter reflector would provide ~8MW.





A 1000m2 TF reflector design with a Kapton layer, stowed using a spiral crease origami folding pattern would have a mass of 235 kg and fit in 1.34 m^3 volume.

A 100-m tall tower made of 2-m diameter inflatable beams , built with a 50 g/m^2 inflatable surface requires ~8 m^3 and ~900 kg.

Tower plus two 40 m-diameter reflectors could be built within the same mass and volume constraints of an MSL-class mission.

Solar Energy Infrastructure Nodes - Functions

Redirect solar - reflectors, mirrors

Convert solar – convert to electrical

Transmit energy – transmit in microwave or laser

Longer distances require conversion/transmision

Storage

Battery recharge if operating in regions beyond reach

Storage in thermal energy

STEM® is **an innovative technology of solar thermodynamic** that uses sand, as a way of thermal energy storage generated from the solar radiation, with the fluidized bed technology (sand mixed with air).
It assures the **continuous operation of the plant even without irradiation**, during the night or with cloudy weather according to the required load curve. The installed module has a capacity of **2 MW thermal of energy.**

- Solar power concentrator for cogeneration
- Fluidized bed technology
- Granular material, coarse dimensions

783 m2

2 thMW each module

270 tons of sand

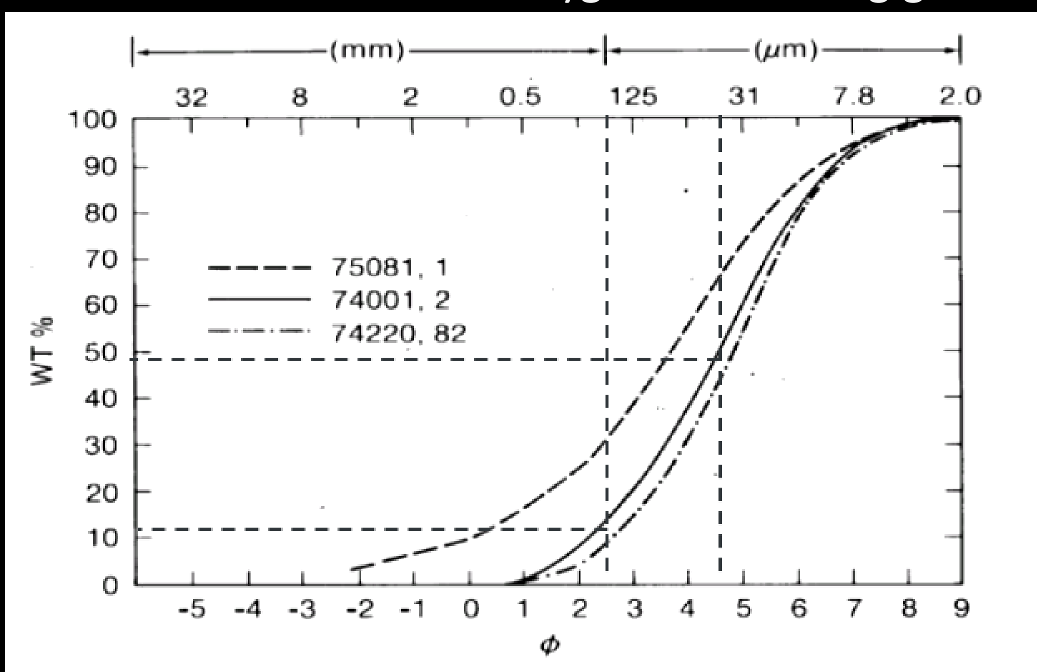
600° C

6h after sunset

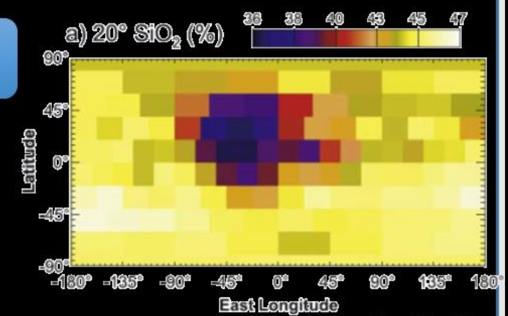
Storage using lunar regolith

50-100 microns
WE CAN USE LUNAR REGOLITH (need air/gas too)
About 10 percent of a lunar soil is greater than 1 mm, 50 percent is greater than 100 microns, and 90 percent is greater than 10 microns (from *Heiken et al. 1974*).

Extracted Oxygen as fluidizing gas



~45%



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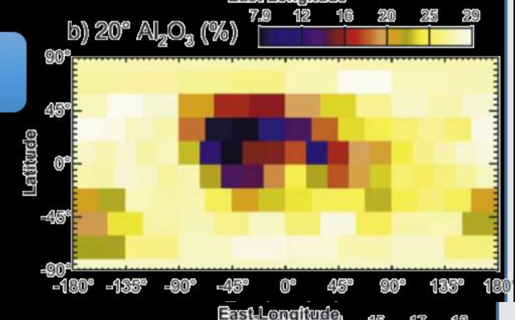

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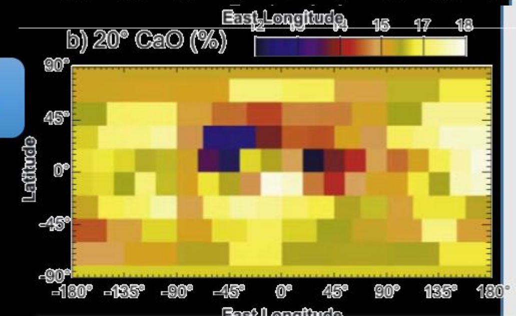

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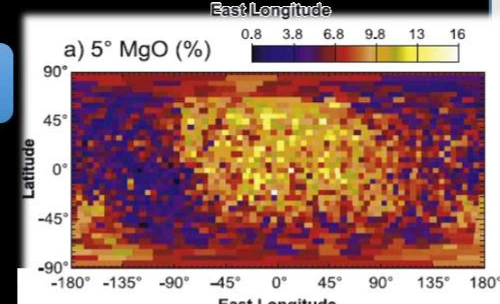


NASA SP-509, Volume 2, Energy, Power and Transport, 1992, pp. 117

Electromagnetic Launch of Lunar Material

By William R. Snow and Henry H. Kolm, NASA SP-509

Introduction

Lunar soil can become a source of relatively inexpensive oxygen propellant for vehicles going from low Earth orbit (LEO) to geosynchronous Earth orbit (GEO) and beyond. This lunar oxygen could replace the oxygen propellant that, in the current plans for these missions, is launched from the Earth's surface and amounts to approximately 75 percent of the total mass. Besides the LEO-to-GEO missions, a manned Mars mission could benefit from this more economical oxygen. The use of such oxygen in a chemical rocket would eliminate the need to develop an advanced non-chemical propulsion technology for this mission. And the shorter trip time afforded by a chemical rocket would also reduce life support requirements.

The reason for considering the use of oxygen produced on the Moon is that the cost for the energy needed to transport things from the lunar surface to LEO is approximately 5 percent the cost from the surface of the Earth to LEO. This small percentage is due to the reduced escape velocity of the Moon compared with that of the Earth. Therefore, lunar derived oxygen would be more economical to use even if its production cost was considerably higher than the cost of producing it on Earth.

nar Oxygen Delivery Orbits and Missions, Snow, Kubby, and Dunbar 1982; Davis 1983; Bilby *et al.* 1987; Snow *et al.* 1988; LSPI 1988). A diagram of the Earth-Moon system showing the orbits and missions for the lunar oxygen delivery concept that we recommend is shown in Figure 12.

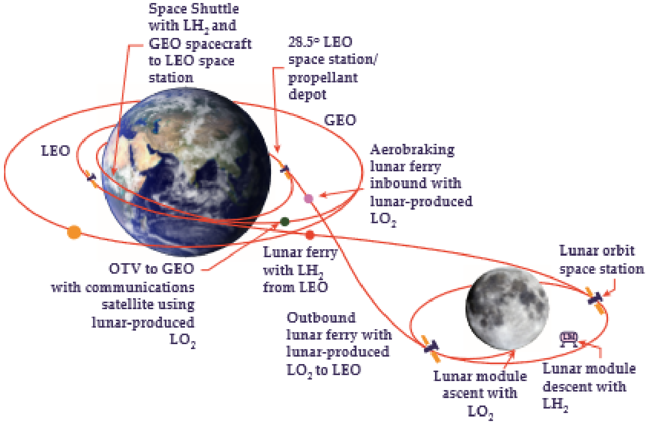


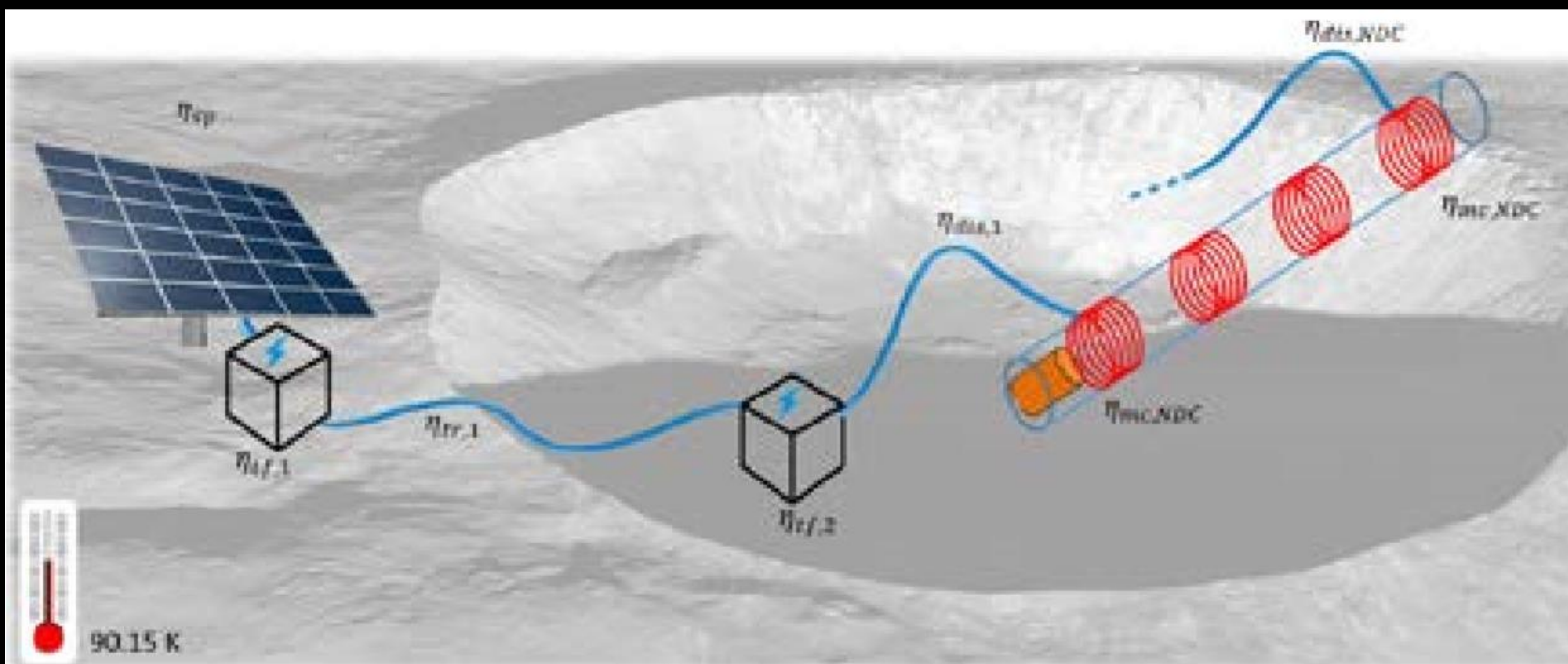
Figure 12 — Lunar Oxygen Delivery Orbits and Missions

The mission scenario starts with the launching of tanks containing 1 metric ton or more of liquid oxygen from an electromagnetic launcher (superconducting quenchgun) on the lunar surface into low lunar orbit

Solar power for an EMG launcher

Electromagnetic launcher at 30 degree angle on the wall of Shackleton crater.

Its operation can be powered by the solar energy



How to deploy Towers

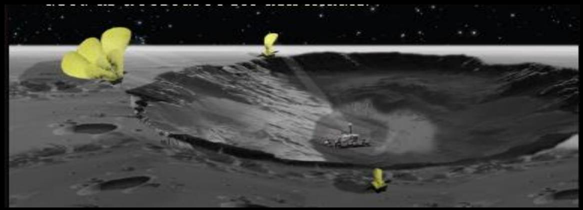
How to get tower in place?

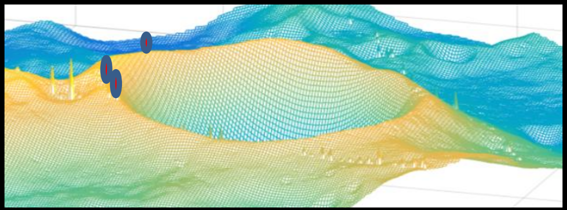
(may land away from peaks, but want to be on peaks)

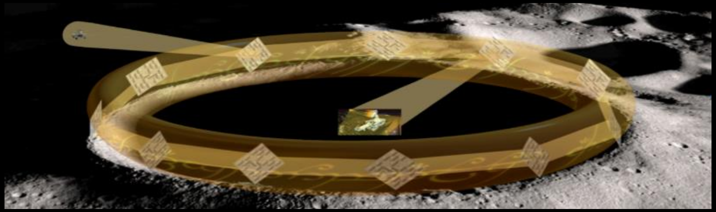
How to service it in case it's needed?

A True Ring of Power

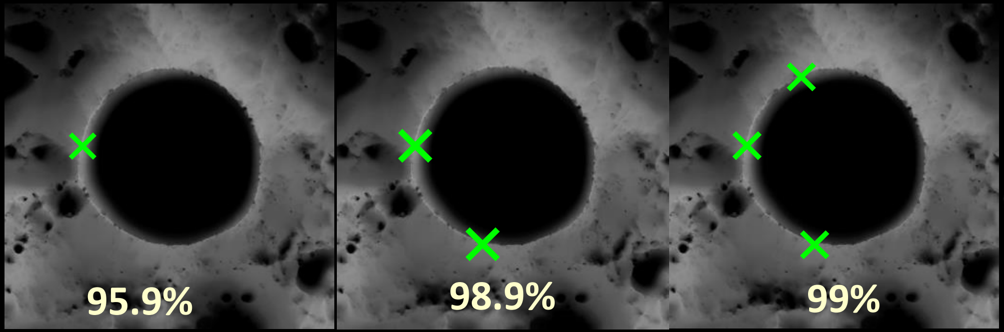
Placing multiple TFs on the circular rim, achieves a ring of Power, able to achieve > 99% **continuous illumination on TFs,** and reflect/beam into the crater.





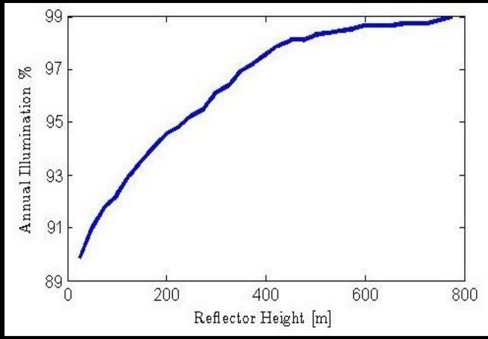


Where to place the TF? How tall? What size?

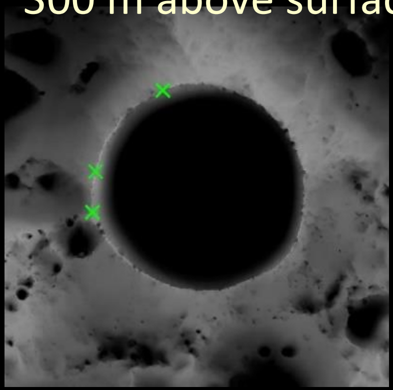


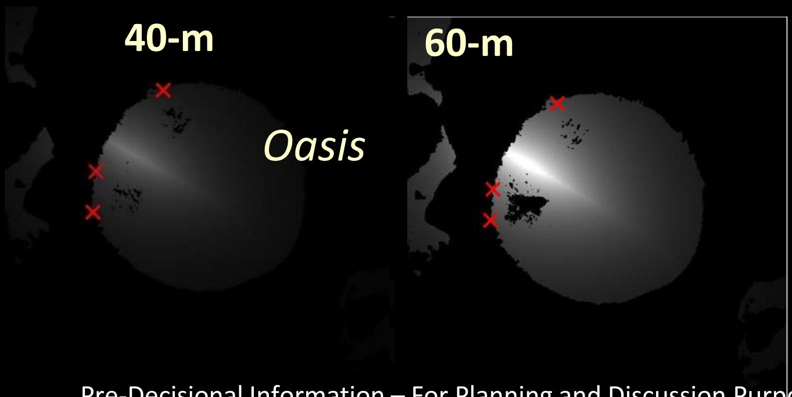
Annual Illumination on at least one point

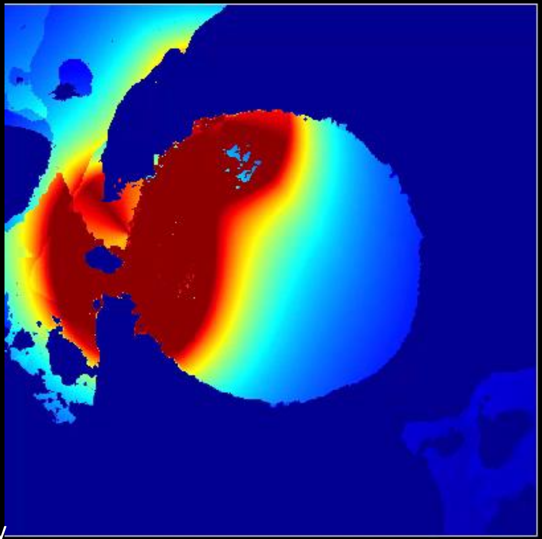
Potential illuminated space (region that can see all reflectors – but they don't reflect everywhere)



300 m above surface

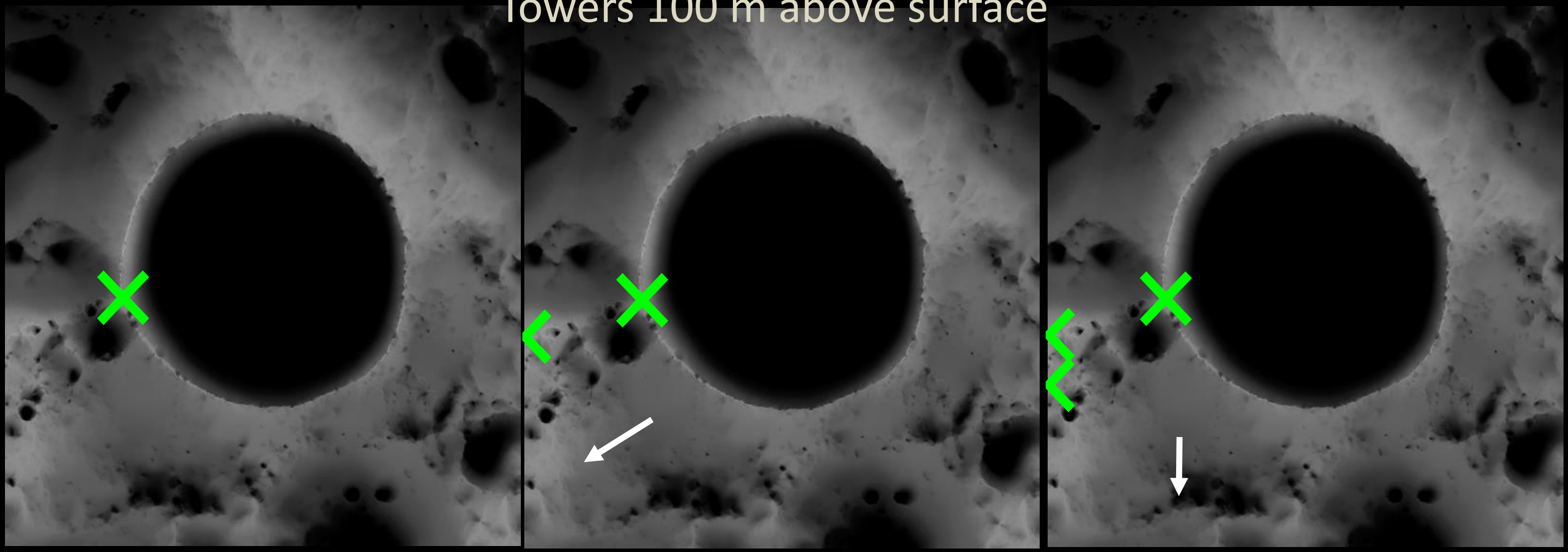






Providing power in oasis outside the crater

Towers 100 m above surface

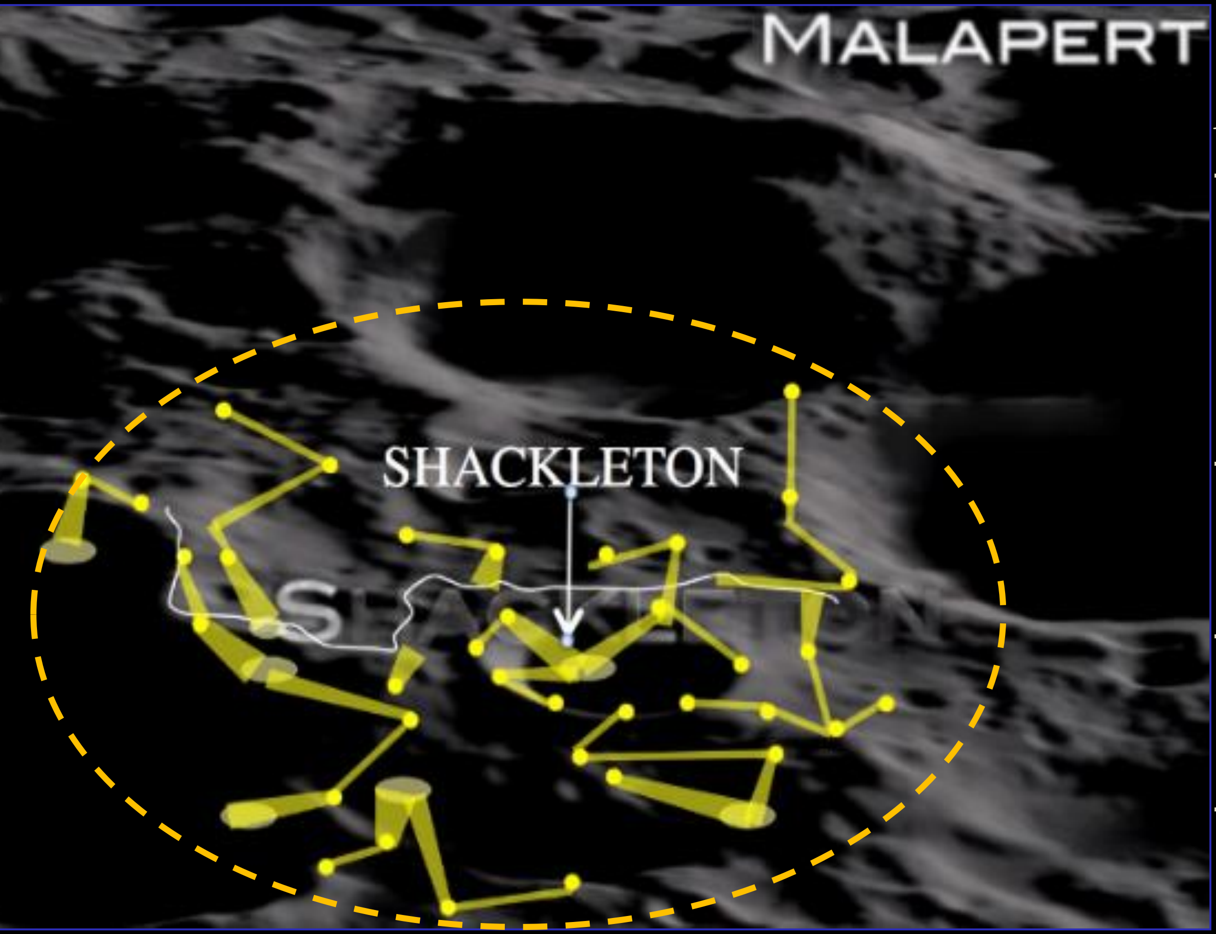


92.0% 98.7% 99%

TFs on the rim would also be able to provide outside the crater.
Also able to achieve almost continuous illumination in regions outside the crater

A Lunar Utilities Infrastructure (LUI)

tens of km from South Pole



A Solar Power Infrastructure (SPI)

- would heat and power many robots at the south pole and provide sunlight for successive missions for both NASA and its partners, for robots and humans
- would lower the barrier to entry for Moon equipment - no thermal concerns;
- would defer costs for thermal till confirmed successful landing
- would no longer be necessary to interrupt missions (hibernate)

A lunar utilities infrastructure (LUI) built on SPI, providing also communications and data, extending for tens of kilometers around the solar south pole.

LUI offers A New Business Model

A new business model: ***pay as you go***
- You don't pay a significant amount before you successfully land (as would be needed if one needs on-board thermal/power) and have it all at risk
- You pay after successful landing and you can pay incrementally, as mission progresses

Specific Technologies

- ISRU/Manufacturing
  - extract resources, Made on the Moon
- Robotic Teams - transform resources create value
- AI - the coordinators – optimize value

Agility, endurance, autonomy (**fitted ones**: bodies and smarts)

Capability

- **Agility:** Navigate difficult terrain with ease
  - Adapt body/mobility to terrain/task
- **Endurance**
  - Survive cold nights
  - Harvest power
- **Intelligence/Autonomy**
  - Solve problems independently: optimize actions

big and strong bodies

Technology

Extendable legs,
reconfigurable shape
Giacometti Robot

Material solutions
System solutions (eg minimize exposed radiating outer surface (fold in),cover by thermal blanket and hibernate.

Multi-criterial optimization (coverage, science value, mission duration with constrained resources such as power).

Multi-robot (MR) teams and swarms (**many fitted ones**)

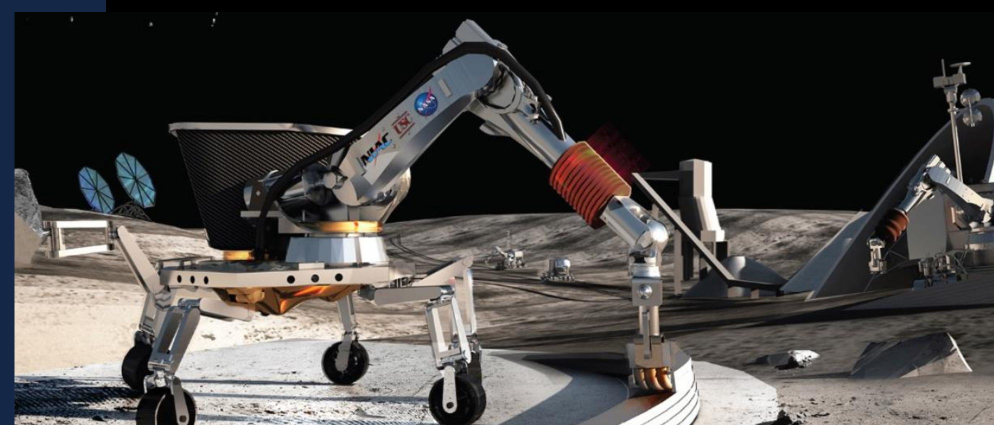
- Advantages of MR teams:
  - Distributed observation
  - Cooperative multi-point action
  - Adaptive system function (e.g. reconfigurable apertures)

- Factors that will facilitate MR teams
  - Packing big and strong robots in small and light packages for launch/transport to surface - adaptive size

Make extensive use of local resources
(make fitted ones, made locally)

- Make robots

-Make infrastructure



Robotic Teams - transform resources create value

From autonomy of single machine to cooperating autonomy of a colony

Working with teams
Team-levels of autonomy

Individual/task specific Levels of autonomy	**Group/team oriented Hierarchy of autonomy**
Telesupervision	*Telesupervision*
Set Objective	Mission Statement
Target Description	High-level Mission Plan
Target Validation	Detail Mission Plan
Target(end-point) Assignment	Group Control
Way-points Control	Leader Control
Direct ('Joystick') Control	Individual Control
Teleoperation	*Teleoperation*

Figure 1. Extension of individual levels of autonomy to a group/team autonomy hierarchy – G-LOA.

Autonomy still involves humans at some stage

From one to one

Many to many

AI - the coordinators – optimize value

The most impactful technologies: super-human robotic intelligence

- Artificial/robotic intelligence will exceed the capabilities of current human-driven exploration, and become the determining factor in conquering space.

- The advancement will depend fundamentally from learning.

  – Learning from humans

    Stoica, Adrian (1995) *Motion learning by robot apprentices : a fuzzy neural approach.* PhD thesis, Victoria University of Technology, Melbourne, Australia

  – Learning beyond statistics/probabilities

Xu Bing's book From Point-to-Point

“All civilizations become either space-faring or extinct.”
– Carl Sagan

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